A Comparison of the Underwater Acoustic Performance of Single Crystal vs. Piezoelectric Ceramic based Cymbal Projectors

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Abstract – The underwater acoustic performance of three same-design 'cymbal' based electro-acoustic projectors are compared. Two of these projectors contain PMN-PT single crystal piezoelectric as the active material while the third utilizes conventional PZT-5H piezoelectric ceramic. The units containing the single crystal material show an improvement in the acoustic source level anywhere from 3 to 15 dB over the frequency band 1-25 kHz. The higher source level is a consequence of the higher drive voltage capability of the single crystal materials. Under appropriate drive conditions, a single crystal cymbal-based projector that is 64 mm thick with an acoustic aperture of 101 mm X 101 mm can generate an acoustic source level of at least 175 dB (re: 1 μPa @ 1 m) from ~ 3 kHz to > 25 kHz.

I. BACKGROUND

The 'cymbal' is a miniature Class V flextensional transducer. The original design, as seen in Fig. 1, was conceived at and patented by Penn State University [1,2]. The standard cymbal consists of a piezoelectric disk that is mechanically coupled to two specially shaped metal caps via an epoxy bond. These caps serve as mechanical transformers for converting the small radial motion of the piezoelectric disk into a much larger axial direction displacement at the apex of the metal caps. Since the piezoelectric disk is poled in the thickness direction, its radial displacement is governed by the magnitude of its piezoelectric charge coefficient, d_{31}. A single cymbal element with brass caps has an in-air resonance frequency of ~ 20 kHz.

The Naval Research Laboratory modified the standard Penn State design by welding threaded studs to the top and bottom caps (Fig. 1). The presence of the studs mass loads the cymbal, reducing its in-air resonance frequency to ~ 13 kHz. Furthermore, by adding additional nuts to the studs, the resonance frequency can be reduced even further (to at least 6 kHz) [3]. More importantly, the studs allow the cymbals to be mechanically fastened between two stiff cover plates to form a very thin panel projector [4-6]. The cover plates provide for a uniform displacement profile across the radiating area [7] as well as adding an additional mass load to the individual cymbals, further reducing their resonance frequency. This thin panel projector design exhibits a resonance frequency in the neighborhood of 1 kHz [5].

In the early stages of their development, cymbal drivers utilized PZT-5H (Navy Type VI) piezoelectric ceramic because of its large d_{31} coefficient of –274 x 10^{-12} m/V [8]. However, because of the material characteristics of such an electrically soft piezoelectric ceramic, e.g. a large displacement hysteresis, high dielectric losses and consequently high heat generation, the use of this material limits the drive level and hence the acoustic output.

Recently, relaxor-based ferroelectric single crystal materials that exhibit extremely large room temperature piezoelectric constants and coupling coefficients that can exceed 90% have been reported [9,10]. These materials achieve their desired piezoelectric properties via engineered domain states. The material selected for this study has a chemical composition of $0.68Pb(Mg_{1/3}Nb_{2/3})O_3$-$0.33PbTiO_3$, which is commonly abbreviated as PMN-33PT. It is a multi-domain single crystal poled along [001], which is off the polarization direction of <111>. Its d_{31} coefficient (-1330 x 10^{-12} m/V) [11] is nearly five times that of a PZT-5H. The higher displacement of the single crystals comes at the cost of a lower generative force. Because single crystals are mechanically softer than their ceramic counterparts, the single crystal has a lower resonance frequency. For comparison, the Young's modulus of PMN-33 single crystal is 8.4 GPa [11], whereas PZT-5H is 62 GPa [8].

Because of the marked improvement in piezoelectric properties that single crystals have over piezoelectric ceramics, they have the potential to markedly improve the performance of Navy transducer systems. The first step, though, is to compare the performance of single crystals in acoustic applications already well established utilizing conventional piezoelectric ceramics. One such device is the cymbal-type flextensional driver.

This paper will compare the underwater acoustic performance of two identical cymbal-based underwater acoustic projector designs, one of which utilizes PZT-5H as the active material, the other PMN-33PT single crystal.

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Fig. 1 Photograph of the top and side views of the PSU type (left) and NRL type (right) cymbal drivers. The scale is ruled in millimeters.

II. PROJECTOR DESIGN

The projector design used to compare the acoustic performance of PMN-33PT single crystals to PZT-5H ceramic consists of an array of 49 cymbal elements with brass endcaps. Titanium is the usual material of choice for the endcaps [3-5,12]. However, because of the lower generative force associated with single crystals as compared to ceramics, brass, which is softer than titanium, was used instead. The cymbals are held around their outer rim in a flexible neoprene rubber mount (Fig. 2a). The rubber mount contains shallow recesses that allow the cymbals to be snapped into place [3,13]. Since the cymbals are held in place at a node (their outside rim), this mounting configuration allows the metal caps to flex freely.

Thin nickel ribbon is used to wire the cymbals together electrically in parallel (Fig. 2b). A Plexiglas® sheet, with a hole situated over the top of each of the cymbals, is glued to each side of the neoprene rubber mount. This assures that the cymbals remain in the same plane as well as provides a means of attaching the cymbal array to the projector housing (Fig. 2c). The completed, caster oil-filled assembly is shown in Fig. 2d. The acoustic aperture is 101 mm x 101 mm.

The conventional PZT-5H cymbal-based projector was designed by the Naval Research Laboratory as a medium power electro-acoustic source for optimal use at frequencies between 5-15 kHz. Its low weight and thin profile make it an ideal candidate for application on small underwater vehicle platforms. This projector design has also been shown to remain operable to water depths of ~ 200 meters with little degradation in acoustic performance [12].

Three projectors were built and compared. One consisted solely of PZT-5H based cymbals. The other two contained only PMN-33PT based cymbals. Fig. 3 shows a comparison of the in-air resonance frequencies of each of the individual cymbal elements in the three projectors.

a)

b)

c)

d)

Fig. 2 Oil-filled cymbal fabrication process – (a) individual cymbals are mounted in a neoprene rubber mount, (b) the individual cymbals are wired together electrically in parallel, (c) the cymbal array is incorporated into a metal housing, and (d) the housing is sealed and filled with caster oil.

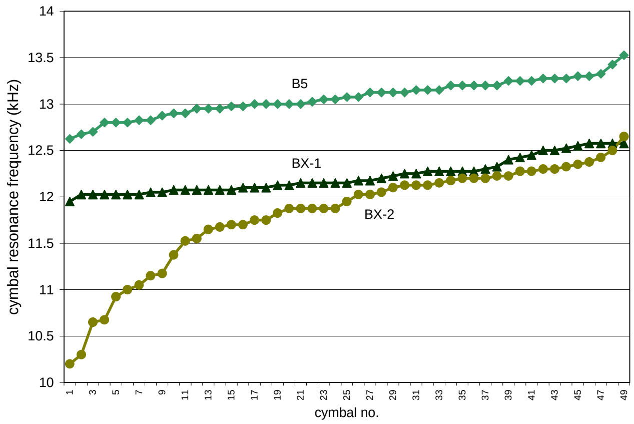


Fig. 3 Variation of the in-air resonance frequency of the individual cymbal elements utilized in Projectors B5, BX-1, and BX-2.

In the PZT-5H cymbal-based projector, designated as B5, the in-air resonance frequencies among all 49 cymbals in the unit varied by less than 1 kHz. The single crystal cymbal-based projectors, designated as BX-1 and BX-2, were deliberately designed such that one unit, BX-1, had a very tight tolerance in terms of cymbal-to-cymbal resonance frequency. In this particular unit, the variation in resonance frequency was only about 0.5 kHz. On the other hand, in unit BX-2 the resonance frequency of the individual cymbal elements ranged from 10.25 kHz to 12.6 kHz. Table I compares the range of capacitance and dielectric loss measured on each individual cymbal in each of the three projectors. Again, single crystal projector BX-1 exhibits the tighter tolerance in terms of capacitance and loss variation as compared to unit BX-2. The reason for building two dissimilar single crystal-based projectors was to determine whether a wide range of properties among the individual cymbals in a given projector significantly affected the overall acoustic performance.

TABLE I

THE CAPACITANCE AND DIELECTRIC DISSIPATION (LOSS) VARIATION AMONG THE INDIVIDUAL CYMBALS IN PROJECTORS B5, BX-1, AND BX-2

Unit	Capacitance (nF) @ 1 kHz				Loss @ 1 kHz			
	min.	max.	avg.	σ_n	min.	max.	avg.	σ_n
B5	1.93	2.78	2.39	0.17	.0120	.0210	.0150	.001
BX-1	2.39	3.56	2.88	0.24	.0030	.0105	.0056	.002
BX-2	1.74	3.76	2.64	0.51	.0034	.0118	.0069	.002

σ_n is standard deviation

III. UNDERWATER CALIBRATION

A. Experimental Procedure

Underwater calibration measurements were conducted at the Underwater Sound Reference Division of the Naval Sea Systems Command located in Okahumpka, FL. The water temperature was 22 degrees C. The projector being evaluated and the receiver hydrophone were two meters apart and at a depth of 12.2 meters. The AC power source was a Kilowatt Amplifier Model LD1-3 from Instruments Inc. Because of the very low coercive field associated with single crystal piezoelectric materials (on the order of 80-120 V_{rms}/mm [10]), a DC electrical bias needs to be applied to the transducer in order to take full advantage of the high strain associated with these materials. A schematic of the bias circuit is shown in Fig. 4. The DC power source was a Sorensen 230-6P-R&D High Voltage DC Power Supply. Unit BX-1 was driven at a duty cycle of one percent (3 pulse/sec, 3 msec pulse length). Units B5 and BX-2 were both driven at a duty cycle of five percent (1 pulse/sec, 50 msec pulse length).

B. Results

Fig. 5 compares the electrical impedance and impedance phase angle for the three projectors tested. These measurements were made with each projector subject to an AC drive field between 206 and 211 V_{rms}. In addition, the DC bias used on both single crystal-based projectors was nominally 300 V. The impedance amplitude (Fig. 5a) was nearly identical for each of the three projectors across the frequency band from 1-25 kHz. There is a slight difference in phase angle (Fig. 5b). There is a resonance in each of the projectors at slightly above 5 kHz. This arises from the flextensional motion of the metal endcaps [14]. Because this resonance is not associated with a pure vibration mode of the piezoelectric disk, the impedance phase angle does not pass through zero degrees.

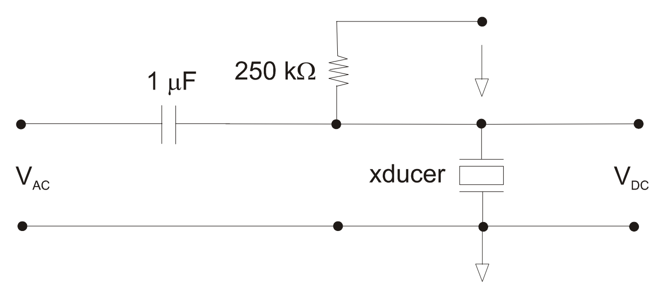


Fig. 4 Schematic of the electrical bias circuit used when driving the single crystal cymbal-based projectors.

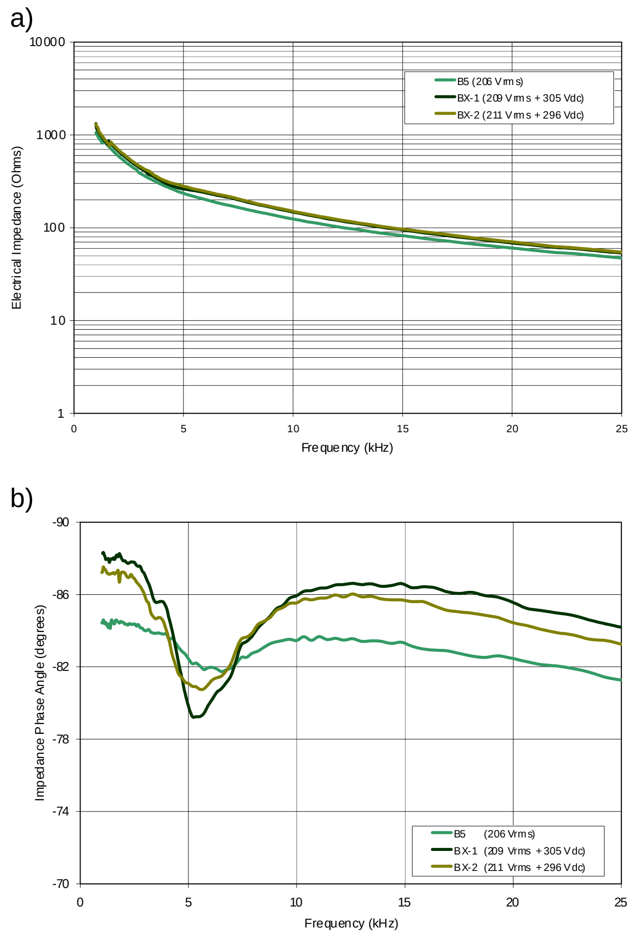


Fig. 5 A comparison of the (a) electrical impedance, and (b) the impedance phase angle for projectors B5, BX-1, and BX-2.

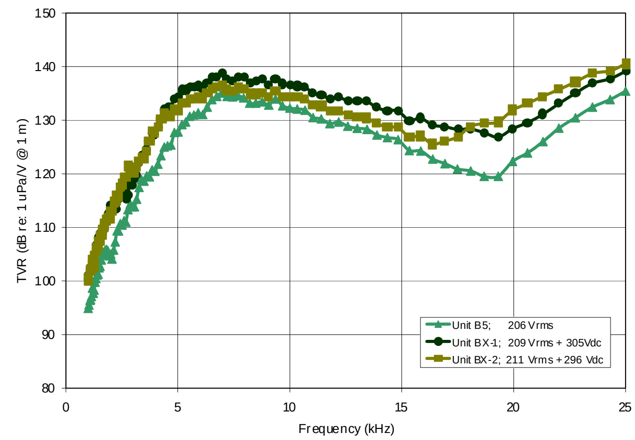


Fig. 6 A comparison of the transmitting voltage response (TVR) of projectors B5, BX-1, and BX-2.

Fig. 6 shows the transmitting voltage response (TVR) measured on units B5, BX-1, and BX-2. In all three cases, the projectors were driven with an AC voltage of nominally 210 V_{rms}. The DC bias on the single crystal-based units was approximately 300 V. Note that units B5 and BX-2 were driven at a 5% duty cycle whereas unit BX-1 was driven at a 1% duty cycle. Below 5 kHz, the difference in TVR between the two single crystal-based projectors is negligible, as expected. However, from 5 kHz to about 17 kHz, Unit BX-1 exhibits a 1-2 dB higher TVR than Unit BX-2. The lower TVR associated with Unit BX-2 is attributed to the wider variation in properties of the individual cymbal driver elements that comprise this projector.

When comparing the PZT-based cymbal projector to Unit BX-1, it is seen that the two TVR curves practically mirror each other, but with the single crystal cymbal-based projector showing an approximately 5 to 10 dB enhancement in TVR across the entire frequency band.

Fig. 7 compares the transmitting power response (*TPR*) of Units B5, BX-1, and BX-2. The transmitting power response of the projectors was calculated from the input rms voltage (*V* in dB) and rms current (*I* in dB), the impedance phase angle θ_z, and measured acoustic source level (*SL*) as:

$$TPR = SL - 10\log\left[10^{\left(\frac{V+I}{20}\right)} * \cos\theta_z\right] \qquad (1).$$

Again, for the three projectors compared in this figure, the drive voltage is nominally 210 V_{rms}. In the case of the single crystal units, a DC bias of ~ 300 V was also incorporated. Below 5 kHz, the *TPR* of Units BX-1 and BX-2 behave as expected and are nearly identical. Above 5 kHz, the curves no longer coincide and from 5-17 kHz, Unit BX-1 has a 2-5 dB higher *TPR*. The lower than expected response from BX-2 is again attributed to the wider variation in BX-2's individual cymbals material properties. The *TPR* curves of B5 and BX-1 nearly mirror each other, but with BX-1 exhibiting a 5-10 dB improvement in *TPR* across the frequency band 1-25 kHz.

Fig. 8 compares the acoustic source level for the three projectors at their respective maximum drive levels. Unit B5 shows the lowest source level among the three, which was expected, due to its low drive level. Unit BX-1 shows the highest acoustic output across the entire frequency band of interest. The data indicate that this unit is capable of delivering a source level of 180 dB from ~ 4 kHz to over 25 kHz.

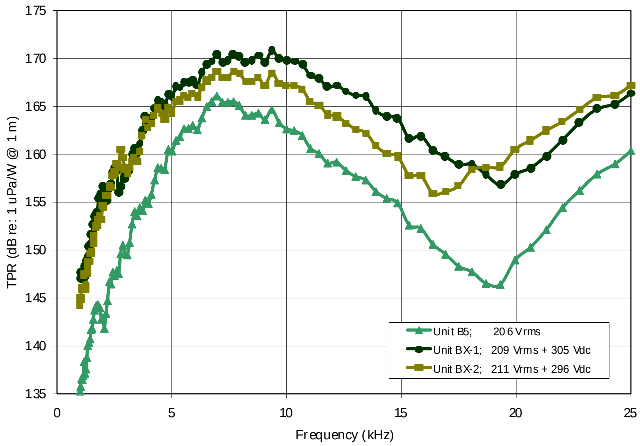


Fig. 7 A comparison of the transmitting power response (*TPR*) of projectors B5, BX-1, and BX-2.

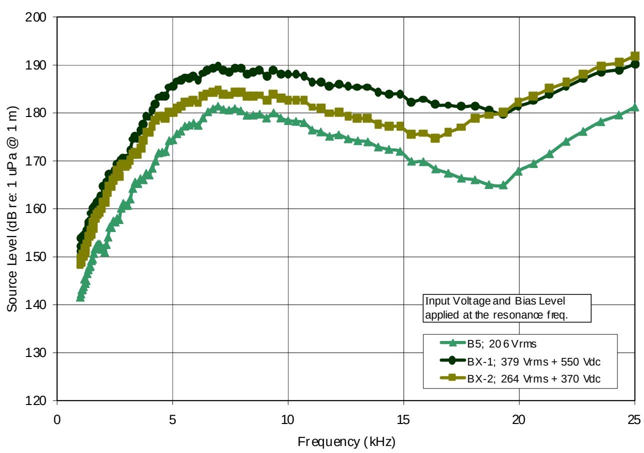
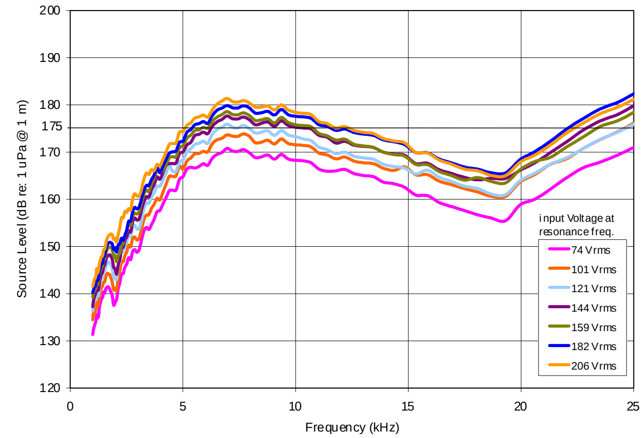


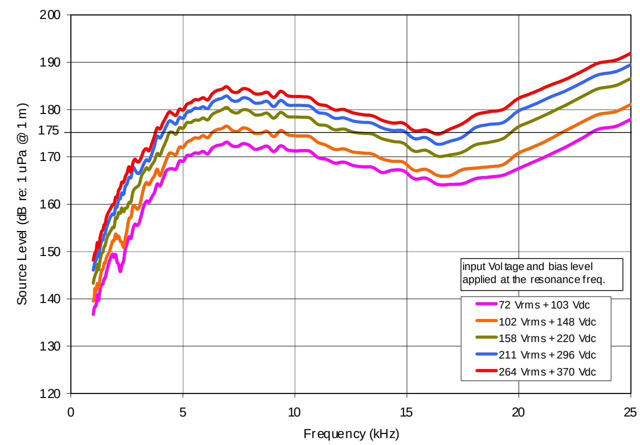
Fig. 8 A comparison of the acoustic source level achieved in projectors B5, BX-1, and BX-2 based on the maximum drive level possible for each unit.

Fig. 9 shows the acoustic source level as a function of drive voltage for the three projectors tested. Units B5 and BX-2 were driven at a duty cycle of five percent and Unit BX-1 was driven at a duty cycle of one percent. Because the electrical impedance and phase angle changes with frequency (Fig. 5), the input voltage shown in the insets is not constant across the entire frequency band. The value recorded in each plot is the input voltage applied at the respective projector resonance frequency only. In fact, the highest voltage seen by projector B5 before distortion was observed in the receive signal was 219 V_{rms} (at ~ 3 kHz). For all three projectors, the source level is linear with drive voltage and there is no shift in the resonance frequency as the input voltage is increased.

(a)



(b)



(c)

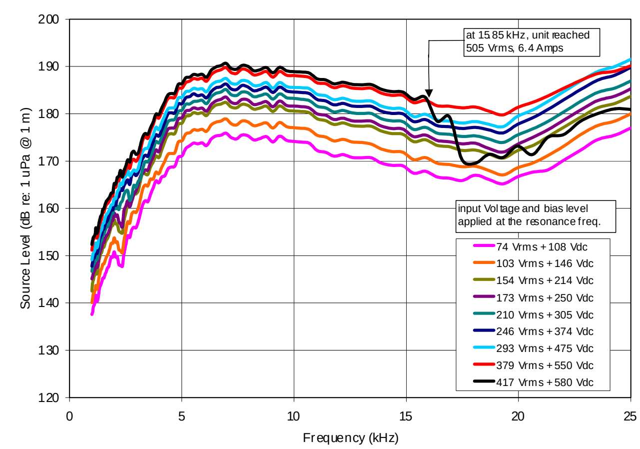


Fig. 9 Acoustic source level as a function of applied voltage for (a) Unit B5, (b) Unit BX-2, and (c) Unit BX-1.

Figs. 9(b) and 9(c) show the acoustic source level as a function of applied voltage for Units BX-2 and BX-1, respectively. In both cases, a DC electrical bias approximately equal to the peak AC voltage ($V_{rms} * \sqrt{2}$) was also applied. Whereas the DC bias voltage remained constant from 1-25 kHz, the AC drive voltage did not (again, because of the changing impedance and phase).

For Unit BX-2, the largest drive voltage at resonance for which a measurement was recorded was 264 V_{rms} with a corresponding DC bias of 370 Volts. However, the largest voltage into the projector was actually 356 V_{rms} (+ 370 V_{dc}) at 25 kHz. An attempt was made to increase the drive level at resonance to 300 V_{rms} + 455 V_{dc} but the projector failed catastrophically.

Fig. 9(c) shows the acoustic source level as a function of applied voltage for Unit BX-1. The highest drive level that this projector could withstand at resonance was 417 V_{rms} + 580 V_{dc}. At 15.85 kHz, the drive level reached 505 V_{rms} + 580 V_{dc} and the projector failed catastrophically. The much higher drive level capability of this projector is attributed to its lower duty cycle. Because of its higher drive level capability, this projector can achieve a source level of at least 180 dB from ~ 4 kHz to > 25 kHz.

The lower maximum drive level in the case of BX-2 as compared to BX-1 is attributed to the former being driven at a higher duty cycle. The higher duty cycle has a detrimental effect on the performance of the single crystals. As also seen in the TVR and TPR, Unit BX-2 generally has a lower acoustic output than Unit BX-1 (when comparing at equivalent drive levels in Figs. 9(b) and 9(c)). The lower acoustic output is attributed to the wider variation in properties of the individual cymbals in Unit BX-2 as compared to Unit BX-1.

Fig. 10 compares the requisite voltage, current, and subsequent electrical power needed to achieve an acoustic source level of 175 dB (re: 1 μPa @ 1 m) in Units B5 and BX-2 across the frequency band from 1-25 kHz. Units B5 and BX-2 are compared because they both were driven with a common duty cycle of five percent. The dashed horizontal lines in Fig. 10(a) indicate the maximum voltages that can be applied to the two projectors, 219 V_{rms} in the case of Unit B5 and 356 V_{rms} for Unit BX-2. These values were ascertained from the experiments that generated Fig. 9. Where these dashed lines intersect the respective voltage curves indicates the frequency band over which the projector can be used. For the case of Unit B5, it can generate an acoustic source level at least 175 dB from ~ 5 kHz to ~ 13 kHz. The single crystal based cymbal projector, on the other hand, is able to produce a source level of over 175 dB from ~ 3 kHz to > 25 kHz. The usable frequency band is more clearly marked in Fig. 10(b), which also shows that the input power required to obtain a source level of at least 175 dB is less than 40 Watts for both projectors.

(a)

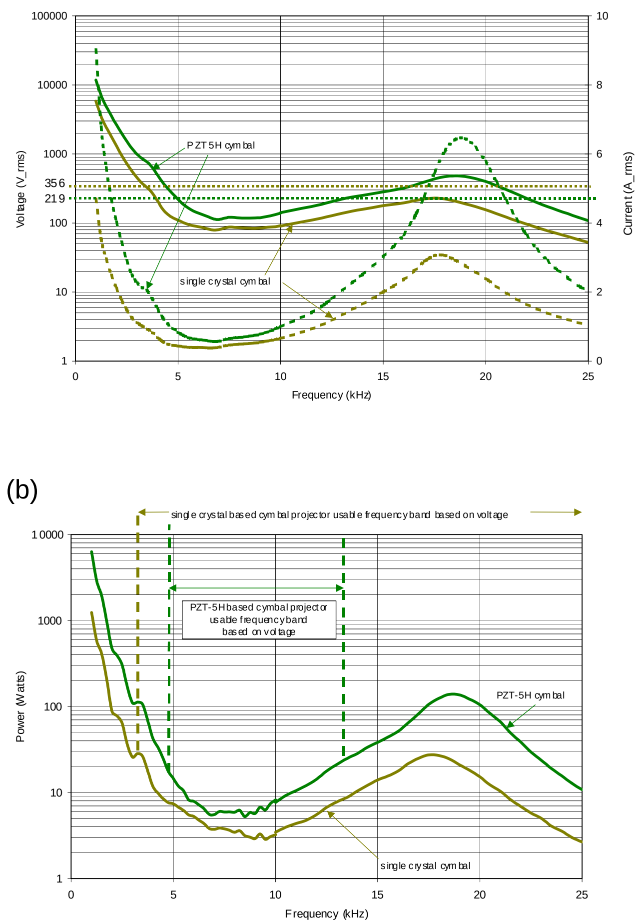


Fig. 10 A comparison of the (a) voltage (solid lines) and current (dashed lines), and (b) electrical power needed to generate an acoustic source level of 175 dB (re: 1 μPa @ 1 m) across the frequency band 1-25 kHz for both a PZT cymbal-based and a single crystal cymbal-based projector.

Fig. 11 shows directivity patterns representative of the three projectors at 5 kHz and 10 kHz. Both match well with prediction and hence are indicative of a well-behaved projector. The beam patterns also indicate that acoustically this cymbal-driven projector may be considered as a baffled piston in terms of radiation behavior. Fig. 12 overlays the 25 kHz directivity patterns for Units BX-1 and BX-2. Although Unit BX-1 shows slightly better on-axis symmetry than does Unit BX-2, overall their beam patterns are pretty similar. Measurements were likely made too quickly and at too large of angular steps to better refine the patterns off the acoustic axis. However, the data do appear to indicate that the greater variability in properties among the individual cymbals in Unit BX-2 as compared to BX-1 is not a significant problem as far as projector directivity is concerned.

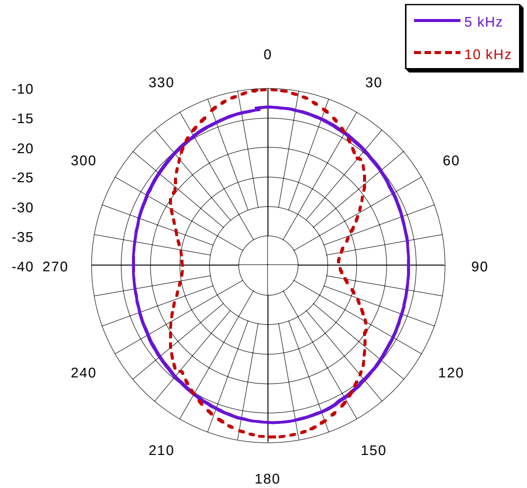


Fig. 11 Directivity patterns measured at 5 kHz and 10 kHz on projector BX-1. These beam patterns are also representative of those from projectors B5 and BX-2.

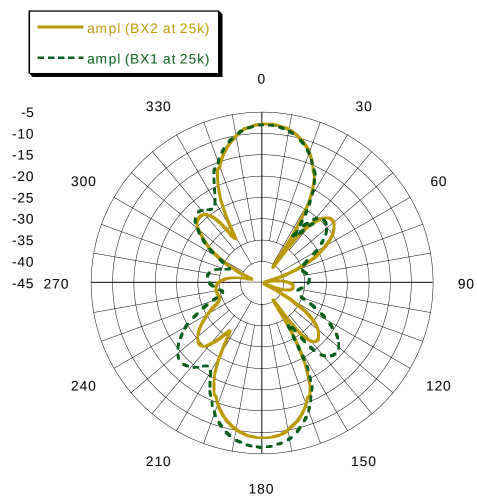


Fig. 12 Directivity patterns at 25 kHz measured on projectors BX-1 and BX-2.

IV. CONCLUSIONS

Cymbal-based projectors that utilize single crystals show better acoustic performance (up to 5-10 dB enhancement in transmitting power response and acoustic source level, depending on the frequency range of interest) as compared to units that use conventional PZT-5H piezoelectric ceramic. The allowable drive voltage for the single crystal-based projectors appears to be duty cycle dependent, with the highest drive voltage being nominally 500 V_{rms}, provided it is coupled with an appropriate DC bias. The projectors are linear and show no shift in resonance frequency with increasing drive voltage. The cymbal-driven projectors are well behaved acoustically and may be considered as a baffled piston in terms of radiation behavior. Maintaining a tight tolerance in properties among the individual cymbal elements that constitute the projector is desirable in order to optimize the acoustic output.

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